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Numerical Models of the ISM

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Abstract. I review recent results from numerical simulations on the structure and dynamics of the ISM, and attempt to put together a coherent dynamical scenario. In particular, I discuss results on 1) the spatial distribution of the gas components, showing that reasonable agreement between simulations and observations exists, but noting that in most models the components are simply defined as temperature intervals, because distinct thermodynamic “phases” do not arise; 2) some statistical issues of the physical fields, like the dependence of the one-point statistics of the density field on the effective equation of state of the gas, the poor correlation of magnetic strength with density, the energy spectrum in weakly and highly compressible cases, and the one point statistics of the velocity field; 3) the effects of spectroscopic observation on distorting the physical structures and results from synthetic observations of the simulations, and 4) several dynamical and thermodynamical issues, such as the (apparently minor) role of the thermal instability in forming and confining clouds, the continuous, rather than abrupt, transition between “phases”, which in turn may be consequences of the dynamics rather than the agents controlling it, the possibility of short time scales (\sim a few Myr) for molecular cloud formation, and the star-gas connection, mentioning that the models generally exhibit self-propagating star and cluster formation, while the stars may drive the medium- and small-scale gas motions, and that a “star formation instability” may induce chaotic behavior of the star formation rate locally. I conclude with a round-up view, and a discussion of the work needed ahead.

1. Introduction

Two of the most influential models of the interstellar medium (ISM) to date are the two- and three-phase models of Field, Goldsmith & Habing (1969) and of McKee & Ostriker (1977, hereafter, MO). These models relied on the then known atomic and radiative heating and cooling processes to provide a self-consistent picture of the ISM in which the concepts of thermal and pressure equilibria played a fundamental role. Another important model was the time-dependent model of the ISM by Gerola, Kafatos & McCray (1974), which was presented as an alternative to the pressure equilibrium two-phase model of Field et al. (1969) but assumed radically different conditions: a constant-density medium under the influence of stochastic, local heating events that should cause strong local

fluctuations of pressure and temperature, because the cooling and recombination times are comparable or shorter than the time between exposure of a given gas parcel to one of those heating events. Note that the MO model also recognized the existence of local fluctuations in the pressure, although it was still based on the premise of “rough pressure balance”.

Nevertheless, both the equilibrium and the time dependent models left out a number of important aspects in the ISM physics. The multiphase equilibrium models essentially neglected the possibility of large pressure fluctuations in the ISM. The time dependent model instead included this possibility as a fundamental premise, but still neglected the fact that such fluctuations should induce motions, which should in general be turbulent and cause strong density fluctuations. The turbulence involves gas motions at all scales which not only provide ram “pressure”, but also mixing, and can produce compressions rather than “support” (e.g., Elmegreen 1993; Ballesteros-Paredes, Vázquez-Semadeni & Scalo 1999a).

Moreover, both the time-dependent and the MO models omitted other sources of pressure in the ISM, such as magnetic fields and cosmic rays. The pressure from these agents is in fact significantly larger than the thermal pressure (e.g., Boulders & Cox 1990). Elmegreen (1991, 1994) has performed a combined instability analysis including self-gravity, cooling and heating, and magnetic fields, but the full nonlinear behavior can only be dealt with by means of numerical simulations of the gas dynamics in the Galactic disk. In this review, I will summarize a variety of results in this area, pioneered by Bania & Lyon (1980), concerning the spatial distribution both on the Galactic plane and perpendicular to it (§2), the one-point and correlation statistics of the physical fields (§3), the comparison between “synthetic” observations of the simulations and actual observations of the ISM (§4), and several dynamical aspects, including the role of thermal and ram pressures, the virial balance of clouds, the nonlinear Q parameter and the star-gas connection (§5). I conclude (§6) with an attempt to present a comprehensive scenario, which should constitute the first step towards a full dynamical theory of the ISM that can take over where the time-dependent and the MO models left off.

Given the focus on HI gas of the present conference, this review concentrates on hydro- and magnetohydrodynamic numerical simulations of the multi-temperature¹ gas in the Galactic disk. Thus, the vast literature existing on numerical simulations of isothermal gas, aimed at the molecular-cloud regime, will necessarily be excluded. The reader is directed to the review by Vázquez-Semadeni et al. (2000) for a discussion of that area current up to 1999, and that by Mac Low & Klessen (2002) for the more recent results. Non-hydrodynamical models of the dynamical systems kind have also been excluded (see, e.g., the review by Shore & Ferrini 1995).

¹In this review the common term “multi-phase” will be avoided and substituted by “multi-temperature”, since, as discussed in §5.1, numerical simulations do not in general support the existence of sharp phase transitions in interstellar gas.

2. Spatial Distribution of the Gas

One of the first concerns of numerical simulations was to show that stellar energy injection through ionization heating, is indeed capable of carving “holes” containing hot ($T \sim 10^6\text{K}$) or warm ($T \sim 10^4\text{K}$) dilute gas, and of producing dense, cool ($T \sim 100\text{K}$) clouds, or in general, what has often been referred to as a “multiphase” medium. However, it is important to note that in all simulations, the temperature spans a continuum of values, and the so-called “phases” are generally defined simply in terms of ranges within this continuum. Studies both parallel and perpendicular to the Galactic plane were conducted. It is also important to note that a general feature of the dynamic, yet statistically-stationary regime into which simulations settle, and which is evident from animations, is that the “clouds” have no long-lasting identity, but instead are continually “morphing”² (i.e., changing shape, stretching, merging with other structures, and splitting apart; see §5.1; Shadmehri, Vázquez-Semadeni & Ballesteros-Paredes, this volume).

2.1. Two-Dimensional Structure on the Galactic Plane

Early attempts to show the generation of a multi-temperature medium, even at very low resolutions in two dimensions (2D) parallel to the Galactic plane, were those by Bania & Lyon (1980), Chiang & Prendergast (1985), and Chiang & Bregman (1988). In particular, Chiang & Prendergast also identified a “star-formation” instability, similar to a thermal instability (Field 1965; Field et al. 1969) around an equilibrium state in which star formation balances mass loss, and stellar heating of the gas balances radiative cooling (see §5). On the plane, self-gravity and later magnetic fields, the Coriolis force and shear were included (Vázquez-Semadeni, Passot & Pouquet 1995; Passot, Vázquez-Semadeni & Pouquet 1995), although still without supernova energy input, and without a thermal instability-inducing cooling function. Moreover, Ballesteros-Paredes et al. (1999a) suggested that, since clouds are really sites of larger-scale converging flows, they should often contain shocks within them, implying that the magnetic field can develop large fluctuations and even reversals. Supernova-like energy input at the highest-density sites was considered by Gazol-Patiño & Passot (1999), who found a filling factor of the hot gas at the midplane of typically a few percent, with occasional excursions of up to $\sim 20\%$. Gerritsen & Icke (1997) gave the radial profiles and mass fractions of the gas and star surface density on the plane, finding that the warm gas becomes the dominant gas component beyond 2 kpc from the center, and that between 2 and 7 kpc the mass fractions remain roughly constant, at $\sim 75\%$ for the warm gas, $\sim 15\%$ for the cold gas, and $\sim 10\%$ for what they called the “lukewarm” gas, with temperatures intermediate between those of the cold and warm “phases”.

In general, in 2D simulations, the cloud morphology is extremely filamentary, the filaments arising where large-scale motions collide and shock. In turn, “knots” form at sites where the filaments collide (see also Wada & Norman 1999, 2001; Chappell & Scalo 2001). Wada & Koda (2001) furthermore find that in

²I first encountered this term in the context of audio production, to denote a continuous transition from one waveform into another.

simulations with a weak bar-like gravitational potential, the pc-scale filaments and clumps may organize into large-scale spirals. Interestingly, the filamentary morphology appears to persist in the 3D simulations of Wada (2001). In these simulations, which do not include the magnetic field, the filamentary structure appears to be the consequence of tidal interactions between clumps formed by the combined gravitational and thermal instabilities. Inclusion of the magnetic field may provide another channel for forming filamentary density structures.

2.2. Vertical structure

Perpendicular to the disk, two main paths of numerical study have been pursued: one assumes that the stellar energy injection maintains a turbulent, convective regime in which the vertical structure of the disk is a consequence of both the buoyancy of the hot gas and the bulk motions induced in the cold medium by the injection of thermal and kinetic energy by the stellar sources. The time average of the instantaneous gas distribution is then reported as the resulting vertical distribution. Most of the simulations in this category have neglected the magnetic field. The other assumes perturbations about an initial magnetohydrostatic equilibrium, as initially proposed by Parker (1966), and has studied the nonlinear evolution of the perturbations.

In the first category, Rosen & Bregman (1995) investigated the average filling factor and density profile of the various “phases” as a function of height above the midplane and of the energy injection rate from supernovae, finding that only injection rates comparable to the observed Galactic rate reproduce the observed vertical distribution of the various “phases”, implying that it is the stellar energy injection rate which is responsible for the vertical distribution. Also, they found that more than one exponential component is needed to model the average vertical density profile, and that their cold gas profile compares favorably to the observational profile of Dickey and Lockman (1990). Using 3D simulations, similar results have been obtained more recently by Gerritsen & Icke (1997), de Avillez (2000) and Wada (2001). The former authors used SPH simulations of the whole Galactic disk to find the scale heights for the cold and warm gas and for two stellar populations as a result of the stellar energy injection, while de Avillez found that, without stellar injection, the disk collapses vertically to a few tens of pc. Wada found that the supernova explosions form a plume-like halo.

In the second, magnetostatic category, recent simulations of the Parker instability in a thick disk have been performed by Santillán et al. (2000) in 2D, and by Kim, Ryu & Jones (2001) and Franco et al. (2001) in 3D. Santillán et al. and Kim et al. concluded that the Parker instability alone cannot be the main formation mechanism of giant molecular clouds in the general ISM, because of the low final density enhancements obtained. However, Franco et al. find that the instability can trigger the formation of such clouds inside spiral arms. The effect of the passage of a spiral arm has been modeled by Martos & Cox (1998), who suggested that it may induce a “hydraulic jump” in which the gas is pushed to higher altitudes as it is shocked upon entering the arm and acquires a higher pressure. Martos et al. (1999) have furthermore suggested that this jump may trigger star formation at high altitude over the midplane (over 500 pc). However, the simulations of Martos & Cox explored only the isothermal

and adiabatic cases (with a model term for the magnetic pressure – but see §3.1) and did not include self-gravity, neglecting the possible triggering of thermal and gravitational instabilities by the shock compression (c.f. §5.1). Exploring this scenario in the presence of those agents will be of great interest.

At a more local level, de Avillez & Mac Low (2001) have shown that mushroom-shaped structures arise naturally and rather frequently in their 3D simulations including supernova energy injection, as a consequence of the buoyancy of the hot gas in supernova remnants, and proposed that these may correspond to similar structures observed in recent HI surveys (e.g., Higgs 1999; Taylor 1999)

Three-dimensional simulations addressing the vertical structure of the Galactic disk including both the magnetic field *and* the energizing role of the massive stars have been scarce so far. Korpi et al. (1999) placed supernovae randomly in regions with densities higher than the average. They discussed the filling factor of the hot gas as a function of height above the plane, finding values $\sim 20\text{--}30\%$ at the midplane, but this factor is highly sensitive to the degree of spatial correlation of the model supernova explosions, becoming larger as the supernovae are less correlated. This probably explains the larger values of the midplane filling factor they found compared to the values reported by Gazol-Patiño & Passot (1999), since the latter authors placed the SNe exclusively at density maxima, making them more strongly correlated. In the simulations of Korpi et al., the magnetic field is initially taken very small, and grows in time, but at the time at which these authors analyzed their simulations, the magnetic pressure was still much smaller than the equipartition value with the turbulent component ($\sim 10^{-3}$). Thus, they did not discuss the relative roles of the stellar energy injection and the magnetic field in maintaining the disk thickness. This remains an open issue.

3. Statistics of the Physical Fields

Given the turbulent, yet statistically stationary nature of the ISM suggested by the numerical models, it is important to understand the statistical descriptors. In this section I discuss work related to various such descriptors.

3.1. The Mass Density Probability Distribution, the Density-Magnetic Field Correlation, and the Role of Magnetic Pressure

The density PDF was found by Vázquez-Semadeni (1994) to have a lognormal shape in numerical simulations of isothermal flows, which are reasonable approximations to the flow regime in molecular clouds. Passot & Vázquez-Semadeni (1998; see also Vázquez-Semadeni & Passot 1999) proposed that the origin of the lognormality is the constancy of the sound speed in isothermal flows. Indeed, in this case, the probability of a given density jump is determined simply by the distribution of velocity jumps in the flow, because the local Mach number, which determines the density jump, is independent of the local density, and depends only on the velocity difference across the shock. Thus, all density jumps belong to the same distribution, and, assuming each jump is independent of the previous and later ones (i.e., that shocks are independent from each other), the Central Limit Theorem can be applied to the logarithm of the density, since

the density jumps constitute a multiplicative process. The width of the PDF is proportional to the rms Mach number. Those authors also found that in the more general case of polytropic flows, in which $P \propto \rho^{\gamma_e}$, where P is the (total) pressure, ρ is the density, and γ_e is in general a parameter reflecting the net behavior of the pressure with density, the density PDF approaches a power law at high (resp. low) densities for $\gamma_e < 1$ (resp. > 1). They understood this in terms of the dependence of the sound speed on density, which, when introduced in the previously-lognormal PDF, gives an asymptotic power law behavior on one side of the PDF (see Nordlund & Padoan 1999 for a related discussion).

In more ISM-like simulations in 2D, including magnetic fields, heating and cooling, the Coriolis force and shear, and localized stellar energy injection, Scalo et al. (1998) and Kritsuk & Norman (2001) have reported PDFs with power-law tails at high densities, suggestive of a total pressure which behaves as if having an effective exponent satisfying $0 < \gamma_e < 1$, possibly due to the contribution of the magnetic field to the total pressure. However, in the purely magnetic, isothermal case, several workers (Padoan & Nordlund 1999; Ostriker, Stone & Gammie 2001; Passot & Vázquez-Semadeni 2002) have found that for cases with intermediate-to-large Alfvénic Mach numbers, the magnetic field appears quite uncorrelated with the density. Passot & Vázquez-Semadeni (2002) suggest that the lack of correlation implies that the magnetic field does not act as a restoring force, and thus does not efficiently act as a pressure, instead acting more as a forcing. This implies that modeling the magnetic pressure by means of a γ_e may be inadequate in the turbulent case. Padoan & Nordlund (1999) have suggested that the lack of correlation is a signature of the intermittency of the field, and pointed out that this is consistent with observations of the magnetic field strength in molecular clouds. Apparently, the lack of correlation is also seen observationally (e.g., Crutcher, Heiles & Troland 2002; Troland & Heiles, this volume).

In non-magnetic, multi-temperature simulations, Wada & Norman (2001) have reported PDFs with a lognormal tail at high densities, and a Gaussian one at moderately low densities. Wada (2001, private communication) has furthermore found a power-law range at very low densities. This could seem at odds with the results of Scalo et al. and Kritsuk & Norman, but upon closer inspection, there is little discrepancy, because most of the PDFs of Wada & Norman can be understood in terms of the various polytropic regimes to which the gas in their simulations is subject. In any case, a detailed study is in order.

The PDF of total projected (*column*) density has been discussed by Ostriker et al. (2001), Vázquez-Semadeni & García (2001) and Burkert & Mac Low (2001). Although these works were aimed at isothermal gas, the results from Vázquez-Semadeni & García should be readily extendable to the non-isothermal polytropic case. They suggested that the column density PDF should not have a unique functional form, but that instead it should transit from the shape of the underlying 3D density distribution (a lognormal for isothermal flows) to a Gaussian, as dictated by the Central Limit Theorem when the contributing sample is large enough. The former (resp. latter) case occurs in the limit of few (resp. many) independent “density” events along the line of sight (LOS), i.e., when the extension of the observed object along the LOS is smaller (resp. much larger) than the correlation length. Under this interpretation, the result of Ostriker et

al. that the PDF is close to lognormal, suggests that molecular clouds may have sizes comparable to the turbulent correlation length, a result used by Burkert & Mac Low (2001) to suggest that molecular clouds receive their energy injection predominantly at the large scales. Observational results on the column density PDF for the HI gas are in need to shed light in this direction for this important component of the ISM.

3.2. The Kinetic Energy Spectrum and the Compressibility of the Gas

The kinetic energy spectrum is one of the most extensively discussed properties of turbulent flows. Simulations of weakly compressible hydrodynamic cases (e.g., Porter, Pouquet & Woodward 1992) and of magnetized incompressible regimes (Cho, Lazarian & Vishniac 2001) give a spectral slope close to the Kolmogorov value of $-5/3$. In the magnetic case, this is consistent with the Goldreich & Sridhar (1995) theory. However, in highly compressible cases, no unique slope has been found, and in fact it appears to be dependent on the degree of compressibility of the flow, given by both the rms Mach number and the effective exponent γ_e . Indeed, for isothermal cases, slopes between -1.8 (Padoan & Nordlund 2000, 3D) and -2 (Gammie & Ostriker 1996, $1+2/3$ D) have been found; the latter value has also been reported for multi-temperature cases in 2D by Passot et al. (1995), and is the one expected for a velocity field dominated by shocks (e.g., Saffman 1968 [sec. 6]; Kadomtsev & Petviashvili 1973). This value is consistent with the observed scaling linewidth-size relation for molecular clouds (see, e.g., Vázquez-Semadeni 1999; Vázquez-Semadeni et al. 2000) found by Larson (1981; see also Blitz 1993 for a summary of more recent results). Observational determinations of the energy spectrum in the HI gas are often suggestive of spectra closer to the Kolmogorov value (e.g., Minter & Spangler 1996; Stanimirovic & Lazarian 2001; Dickey et al. 2001), but sometimes they are not (e.g., Deshpande, Dwarakanath & Goss 2000). It is indeed quite possible that the warm neutral and ionized gas exhibit a behavior closer to incompressible Kolmogorov turbulence while the molecular gas is much more compressible, because the cooling time in the former is comparable or larger than the dynamical time, while it is much shorter in the molecular regime. This implies that the behavior in the diffuse gas may be closer to adiabatic (and therefore only weakly compressible) (Kritsuk & Norman 2001; Sánchez-Salcedo, Vázquez-Semadeni & Gazol 2002).

3.3. The Velocity Probability Distribution

An important statistical descriptor that has been discussed mostly in the context of molecular clouds, but that is in principle equally important in other regimes in the ISM, in particular the HI gas, is the PDF of the velocity (vector) field. In the case of incompressible turbulence, the velocity PDF is known to be nearly Gaussian, while that of the velocity *gradient* (or velocity difference across positions in a map) is closer to exponential (e.g., Frisch 1995). Observationally, only the line-of-sight component of the velocity is available, and only in projection, and so both line profiles (Falgarone & Phillips 1990; Falgarone et al. 1994) and PDFs of the line velocity centroids (Miesch & Scalo 1995; Lis et al. 1996, 1998; Miesch, Scalo & Bally 1999) have been proposed as estimators of the line-of-sight velocity PDF. Falgarone et al. (1994) showed that the

line profiles of weakly compressible turbulence have similar moments to those of ^{12}CO and ^{13}CO observational data, while Lis et al. (1998) found that the line centroid *difference* PDFs of weakly compressible turbulence are also similar (non Gaussian) to those of CO data. From these results, this group has suggested that the regime in molecular clouds is only weakly compressible, and dominated by vortical motions.

On the other hand, Miesch & Scalo (1995) and Miesch et al. (1999) have found that the PDFs of the line centroid themselves (not of the differences) in both archival HI data and in molecular-line observations of several star forming regions are also non-Gaussian, with nearly exponential tails, in sharp contrast with the Gaussian PDF for the velocity characteristic of incompressible or weakly compressible turbulence. Miesch et al. further pointed out that images of the largest-magnitude centroid velocity difference are less filamentary than expected for weakly compressible cases. From these results, this group concluded that the turbulence in molecular clouds is highly compressible. The rationale here is that the non-Gaussian velocity increment PDFs would be common to both the compressible and incompressible cases, and therefore not a good discriminator between the two, while apparently the non-Gaussian centroid PDFs are exclusive of the (proposed to be highly compressible) molecular cloud turbulence. The 2D numerical simulations of a pressureless gas with (small-scale) stellar energy injection of Chappell & Scalo (2001) support this view, giving exponential velocity PDFs. However, the 3D simulations of self-gravitating, isothermal turbulence forced at large scales of Klessen (2000) give nearly Gaussian velocity centroid PDFs. The reason for this discrepancy is unclear, and may reside in the different scales of energy injection in the two sets of simulations, or in the greater compressibility of the pressureless simulations (which may actually be a better model of the cool atomic gas in the ISM). Clearly, this remains an open issue, both numerically and observationally, especially concerning the HI gas in the ISM.

4. Synthetic Observations of the Models

An important application of numerical models of the ISM consists of “observing” them in a manner similar to how actual observations of the ISM are performed. Much of the work in this direction has been oriented towards the molecular cloud regime, and thus is out of the scope of this review, but the interested reader is referred to the recent work of Padoan, Mac Low, E. Ostriker, Stutzki and collaborators. Here we discuss some applications to the global ISM, and molecular-cloud work only when it has a direct impact on the global ISM.

One early result found by Burton (1971) and Adler & Roberts (1992), albeit somewhat ignored until recently, is that structures in position-velocity (PV) space often do not correspond to actual, connected structures in physical, 3D space, but simply to chance superpositions of disconnected structures along the LOS (see also Ballesteros-Paredes et al. 1999a; Pichardo et al. 2000; Ostriker et al. 2001; Ballesteros-Paredes & Mac Low 2001; Wada & Koda 2001). This effect is expected to be especially important in the HI gas, given that its emission is mostly optically thin and widespread.

Pichardo et al. (2000) have recently found two other related results concerning the structure seen in velocity channel column density maps. First, as foreseen by Burton (1971), those authors found that the morphology in the channel maps shows a somewhat greater resemblance to that of the *LOS-velocity* field than to that of the density field. This result, together with that of Lazarian & Pogosyan (2000; see also Lazarian, Pogosyan & Esquivel, this volume), that the spectral index of the “emissivity” (strictly speaking, of the column density) in velocity channels of spectroscopic observations depends on *both* the spectral indices of the density and velocity fields, constitutes strong evidence that the structure of the LOS-velocity field plays an important role in determining the structure in velocity channel maps. The numerical simulations were also used by Lazarian et al. (2001) to test the predictions of Lazarian & Pogosyan (2000), confirming them to within 10%.

Second, Pichardo et al. found that the “emissivity” power spectrum in velocity channels continues to have substantial power even at scales small enough that both the density and the velocity spectra have started to decay, suggesting that the velocity segregation imposed on the column density by the spectroscopic observation procedure introduces some spurious small-scale power of its own, unrelated to the structure existing in the 3D physical space. Henney & Vázquez-Semadeni (2002) interpret this as the result of the formation of *caustics* (surfaces of large intensity in PV data cubes) due to the contribution of finite-extent regions along the LOS to vanishingly thin velocity channels. This effect may constitute an alternative or complementary explanation to the one proposed by Deshpande (2000) for the reported observations of structures at very small scales (10-100 AU) in HI absorption studies (see references in Deshpande’s paper), which was based on the suggestion that neighboring lines of sight contain contributions from even the largest scales (in the LOS direction), which account for the variability from one LOS to a neighboring one.

A different kind of synthetic observation of numerical simulations was given by Rosen, Bregman & Kelson (1996), who compared strip scans of the integrated “emission” (total column density) of cold and hot gas in different locations in their simulations to strip scans of HI and X-ray emission. They concluded that the best matches were provided from locations in hot bubbles, reinforcing the idea of the Sun being in such a location. They also found examples of both correlation and anticorrelation between the HI and X-ray emission, with a slight statistical preference for anticorrelations.

5. Dynamical Issues

One of the main advantages of the numerical simulations is that all the physical variables are known everywhere in space and at all times. This allows for a detailed study of the forces acting to create the structures, the degree to which the structures are transient or bound, and the feedback effects between the stars and the gas, among many other issues. Below, we discuss some of them, after noting that, in general, the regime suggested by the simulations is analogous to Kolmogorov turbulence, in the sense that it is the *statistics* of the flow that remain constant, even though the state is highly dynamical, and individual structures are transient. Note, however, that that is probably where the

analogy ends, as interstellar turbulence is highly compressible (at least in cool and lukewarm regions), magnetized, and is forced over a wide range of scales, rather than only at the largest scales (see, e.g., Scalo 1987; Norman & Ferrara 1996; Vázquez-Semadeni et al. 2000). Moreover, in the compressible case, the turbulent cascade, if present, is likely to have “leaks” from all scales down to the dissipative scales via the shocks (Kadomtsev & Petviashvili 1973), contrary to the energy-conserving cascade of incompressible turbulence.

5.1. Dynamics and Thermodynamics of the ISM

One of the fundamental premises of the two- and three-phase models of Field et al. (1969) and MO was that of pressure balance in the ISM, so that cool, dense HI clouds are confined by the pressure of their warmer, more diffuse surroundings, even though in the MO model clouds form in the compressed layers of expanding supernova remnants. However, ever since the work of Bania & Lyon (1980), hydro- and magnetohydrodynamical numerical simulations have shown that many features of the ISM, including the thermal distribution, can be reproduced solely by the action of stellar kinetic energy injection on the ambient gas. In other words, it is important to determine whether (or when) the relatively low variability (a few orders of magnitude, compared to the variations by many dex of the density and temperature) of thermal pressure is the cause or the effect of the interstellar density and velocity structure.

A first piece of evidence was provided by the simulations of Chiang & Bregman (1988), Rosen & Bregman (1995), Vázquez-Semadeni et al. (1995) and Passot et al. (1995), which contained no thermally-unstable temperature range (although the Passot et al. simulations did contain a constant-pressure temperature range with thermal $\gamma_e = 0$), yet they produced realistic clouds and intercloud structures that formed as a consequence of turbulent compressions induced by the stellar energy input. The main differences with the MO model are that the clouds in the simulations do not only arise in shells around stellar sources, but instead the whole medium is in a turbulent state in which compressions are not necessarily the direct result of an expanding shell, and that, being formed by dynamical compressions, the clouds are continually changing shape, merging, getting stretched and disrupted (“morphing”), rather than being “confined” in any way. This is reflected in virial-balance analyses of numerical simulations, which show that the second time derivative of the moment of inertia of clouds in the simulations, far from being near zero, is generally much larger than the contributions from the thermal, kinetic, magnetic and gravitational energies, and instead has its major contribution from moment of inertia flux through cloud boundaries (Ballesteros-Paredes & Vázquez-Semadeni 1997; Shadmehri et al., this volume). Of course, simulations including self-gravity (Passot et al. 1995; Wada & Norman 1999, 2001) show the existence of gravitationally contracting large-scale structures (especially since a small γ_e reduces the Jeans length; Tohline, Bodenheimer & Christodolou 1988; Elmegreen 1991; Vázquez-Semadeni, Passot & Pouquet 1996), as well as of collapsing small-scale ones. Meanwhile, the internal structure of the giant cloud complexes is continually reshaped by the stellar energy injection. One could argue that the clouds are confined by turbulent pressure, but this would be misleading, as turbulence contains large-scale chaotic motions (at the scale of the whole cloud)

which involve the distortion, and in general, transient character of the clouds (Ballesteros-Paredes et al. 1999a).

An important consequence of this turbulent scenario is that it raises the possibility of molecular clouds having formation times (of order a few Myr) shorter by factors of at least half an order of magnitude than previous estimates (e.g., Blitz & Shu 1980), assuming they form from turbulent accumulation of neutral gas (Ballesteros-Paredes, Hartmann & Vázquez-Semadeni 1999b; Elmegreen 2000). In the scenario of Ballesteros-Paredes et al. (1999b), molecular clouds form from larger-scale converging flows in the HI gas that therefore have larger velocity dispersions than those normally associated to the molecular gas (because larger scales have larger velocity dispersions in most turbulent flows). A key issue, however, is that most of the accumulation process may occur in the atomic phase, and only when the column density has reached high enough values does the molecular phase appear (Hartmann, Ballesteros-Paredes & Bergin 2001), eliminating concerns that in such short times not much accumulation can be achieved unless the density of the initial medium is already (too) large (Pringle, Allen & Lubow 2001). The short “formation” time scales refer only to the time after molecular gas appears.

In this dynamic scenario, the relatively weak variability of the thermal pressure in the global ISM is simply a consequence of cooling and heating functions that imply a slow variation of the thermal-equilibrium pressure with density, while the density field is driven by the turbulence, which in turn is powered by the presence of many local heating stellar sources. Indeed, Vázquez-Semadeni et al. (1996) noticed that, if the cooling times are short compared to the dynamical times and the cooling can be approximated as a (possibly piece-wise) power law, the gas follows a nearly polytropic behavior in which $P \propto \rho^{\gamma_e}$ for a power-law cooling function, with $0 \lesssim \gamma_e \lesssim 1$ for $100 \lesssim T/\text{K} \lesssim 8000$ (Scalo et al. 1998). Note that a thermally unstable range would have $\gamma_e < 0$. Certainly, the functional form of the pressure feeds back on the flow, but mainly to determine the response of the density field to the turbulent compressions, as evidenced by the dependence of density the PDF on γ_e (Passot & Vázquez-Semadeni 1998; see §3.1). Of course, the pressure near stellar injection sites is much larger than that on the average ISM, as essentially they may be regarded as either lying on a different equilibrium between the cooling and the local stellar heating (which is much larger than the diffuse background heating), or completely outside of thermal equilibrium, if the dynamical times are short enough. In the simulations of Passot et al. (1995), which included only OB-star ionization-like heating, the pressure in “HII” regions was ~ 10 times larger than the average. The simulations of Mac Low et al. (2001), which included supernova energy input, exhibited pressure variations of up to three orders of magnitude. However, the stellar heating is a relatively local phenomenon, which serves mostly as the forcing for the global ISM (Avila-Reese & Vázquez-Semadeni 2001), while the large fraction of the volume that is not under the direct influence of the sources has a pressure determined essentially by the turbulent density fluctuations through the applicable cooling and heating laws.

On the other hand, ISM simulations including a thermally unstable temperature range between the cold and warm “phases” show density PDFs without clear signs of bimodality, as would be expected for actual phase segregation

(Vázquez-Semadeni, Gazol & Scalo 2000; Wada & Norman 2001; Kritsuk & Norman 2001), and temperature PDFs which, although bimodal, contain significant amounts of gas in the thermally unstable range (Gazol et al. 2001; Kritsuk & Norman 2001; see also Gerritsen & Icke 1997); the same effect is seen in the plots of Korpi et al. (1999), although they did not discuss it. The multimodality of the temperature PDF does not necessarily signal the existence of phases, but simply of heating and cooling processes which favor certain values of the temperature as a function of density. The simulations of Korpi et al. (1999), which include supernova heating, and thus hot ($\sim 10^6$ K) gas, have roughly flat density PDFs except for a pronounced peak at the density of the hot gas, indicative of the relatively large relative filling factor of this temperature range, but still do not show significant signs of “phase” segregation. For there to exist real phase segregation, a discontinuity must occur in one or more of the thermodynamic variables. However, in the simulations there are no such discontinuities (within the numerical resolution and smoothing of discontinuities), and instead the flow appears as a continuum, with the only discontinuities being dynamical shocks. An exception is the case of the simulations by Hennebelle & Péroult (1999, 2000) and Koyama & Inutsuka (2000), who studied the triggering of thermal instability by shocks passing through initially stable gas. However, these authors did not consider the case of a fully turbulent ISM in the presence of other forces besides the thermal pressure gradient. Instead, although further testing at higher resolution is still necessary, the simulations of the fully turbulent ISM strongly suggest that the “unstable” range is actually quite populated in the ISM. A number of observational works point in the same direction (e.g., Dickey, Salpeter & Terzian 1977; Heiles 2001, this volume), although these require further confirmation themselves (see Miville-Deschenes, Hennebelle & Péroult, this volume, for an opposing view).

The mechanism responsible for the at least partial inhibition of the thermal instability is not quite understood so far. Magnetic pressure possibly plays a role (but see §3.1), and velocity fluctuations may inhibit the instability if they have shorter time scales than the cooling time, a phenomenon which is most likely to occur at small spatial scales and/or low densities (Sánchez-Salcedo, Vázquez-Semadeni & Gazol 2002). It is interesting to note that a similar result has been recently reported for the Parker instability, which apparently can be partially or completely suppressed by the presence of fluctuations in the magnetic field (Kim & Ryu 2001). Also, simple continuous recycling from one phase to another may imply the existence of a persistent population of gas traversing the unstable regime, as suggested by Lioure & Chièze (1990).

A complementary point of view is that of Wada, Spaans & Kim (2000), who have recently proposed that the pure gravitational instability, aided by thermal instability, is capable of the formation of large low density regions (“voids”) in the global ISM, which, in their picture, correspond to (some of) the observed HI holes in galactic disks. This is not inconsistent with the previous view of shaping the interiors of giant cloud complexes through the turbulence powered by stellar energy injection. Indeed, the largest cloud complexes may be gathered together by large-scale processes such as gravitational instabilities or the passage of spiral density waves, necessarily leaving behind, by simple mass conservation, large cavities which in fact must occupy large volumes, due to their lower densities. On the other hand, the stellar energy input, which is most likely dissipated

within relatively short distances from the injection sites (Avila-Reese & Vázquez-Semadeni 2001), can have mainly the role of shaping the complexes' interiors. Wada et al. distinguished between stellar-carved cavities, which should be filled with hot gas, and instability-carved ones, which should be filled mostly with warm gas.

The nonlinear development of gravitational instability in magnetized galactic disks has been recently studied by Kim & Ostriker (2001a,b). These authors note that the amplification of non-axisymmetric perturbations in the presence of shear saturates in linear theory, and that thus any Q threshold for nonaxisymmetric gravitational runaway must originate from nonlinear effects. In this context, they numerically estimate the threshold values of Q in the nonlinear case. They also distinguish between the mechanisms operating behind the modified swing amplification and the magneto-Jeans instability.

An interesting point to note is that even in works without stellar energy injection, the outcome of the development of the various instabilities is often a chaotic, or turbulent, medium (Wada et al. 2000; Kim, Ryu & Jones 2001; Kim & Ostriker 2001a,b; Koyama & Inutsuka 2001; Kritsuk & Norman 2001), and so these large-scale instabilities can also be sources of the internal turbulence of the cloud complexes (see also Sellwood & Balbus 1999 for an analytic discussion of the magnetorotational instability powering turbulence in HI disks).

5.2. The Star-Gas Connection

In general, most simulations including non-random prescriptions for star formation (SF) show that it self-propagates and, when other agents such as self-gravity and cooling are also included, spontaneous SF occurs too (e.g., Chiang & Prendergast 1985; Vázquez-Semadeni et al. 1995). Moreover, as has been noted repeatedly, the stars in the simulations provide the energy feeding the gas motions, and a feedback cycle, analogous to that of Oort (1954), is established. However, the cycle is highly chaotic locally (Vázquez-Semadeni et al. 1995, Passot et al. 1995; Gazol-Patiño & Passot 1999; Wada & Norman 2001; see also Shore & Ferrini 1995), and depends on global quantities such as the mean magnetic field strength, and on stellar properties such as the energy deposited per stellar source (Passot et al. 1995; Gerritsen & Icke 1997; Gazol-Patiño & Passot 1999). Other properties of the SF process, such as the slope of the two-point correlation function describing the clustering of young stars, can also be accounted for by this type of numerical models (Scalo & Chappell 1999). Additionally, Chappell & Scalo (2001) have studied the ratio of present to past-average SF rate as a function of various parameters in their simulations, finding, among other results, that starbursts can only occur when the past-average rate is low or the system is small, that the broad distribution of this ratio in late-type systems can be understood as a result of either a small size or a small metallicity, which imply that larger expanding shell column densities are required for gravitational instability, and that exponential tails in the velocity distribution are due to multiple shell interactions, not individual stellar winds.

It is worth noting here that the “star formation instability” identified by Chiang & Prendergast (1985), which was one of the few attempts to investigate

analytically the star-gas interplay within a hydrodynamic approach³, has not been discussed in recent years, even though its effect may be present in all models with self-consistent prescriptions for star formation, possibly explaining its chaotic evolution. Another important connection that has not been considered in numerical models is the excitation of density and velocity perturbations in the gas by the gravitational effect of the stars (Kegel & Völk 1983). These issues certainly deserve further investigation.

6. Conclusions: the Emerging Scenario and the Work Ahead

In this review I have summarized a large body of results derived mainly from numerical simulations of the ISM, which have allowed workers to capture many of the complex dynamical aspects of ISM structure and evolution. The numerical models have suggested a much more complex ISM than a simple three-phase medium in pressure equilibrium. Instead, a turbulent continuum has emerged, apparently without sharp phase segregation, and in which turbulent ram pressure is mostly responsible for cloud formation within the large complexes, while strong thermal pressure imbalances due to local stellar energy injection are responsible for powering the turbulence through expanding shells, although otherwise the near constancy of the thermal pressure has little effect in confining density structures, since *the absence of a pressure gradient does not imply that inertial motions cannot exist*. The medium is not simply a collection of overlapping shells with clouds forming in their compressed layers, but instead is globally turbulent, with shells and all structures in general “morphing” and merging into the global turbulence. At the largest scales, combined gravitational, magnetic and thermal instabilities appear to contribute, together with spiral density waves and supershells, to the formation of the largest complexes and perhaps voids, as well as possibly feeding the turbulence from the largest scales.

The individual structures being transient, the appropriate description for the global structure is statistical. Some statistical measures of the flow (the density PDF and the energy spectrum) depend on the cooling ability of the flow, which in turn determines its compressibility. Since this in turn determines the ability to form gravitationally bound structures through compressions, and therefore stars which feed the turbulence, a full feedback loop clearly exists analogous to the old Oort (1954) cycle.

However, as this review probably makes evident, the body of results is highly scattered, and a coherent, global theory of the ISM is still lacking. Such a theory should be able to predict fundamental statistical indicators of the ISM such as its topological properties (i.e., the statistical distribution of the mass and other physical quantities), the rate of production of collapsing objects (the star formation rate and its efficiency) and the mixing rate of the processed chemical elements, as well as the thermal and radiative properties of the various temperature and density regimes, all as a function of simple input physics, such as the total available mass and angular momentum, the atomic processes determining

³Many attempts have been made in the context of the dynamical systems approach to ISM models; see, e.g., Shore & Ferrini 1995

the cooling rates, and the energy injection per source. Note that, in principle, even “parameters” such as the energy injection rate and the scale of injection, should be derivable from the theory (or model), because the sources in this case are linked to the flow dynamics, as is the case of large-scale instabilities and of the star formation rate. Many of the physical variables are expected to be highly fluctuating locally, and the prediction of both average (see, e.g., Blitz, this volume) and typical fluctuation values is crucial. Simulations including all relevant physical ingredients (self-gravity, disk rotation, magnetic fields, cosmic rays, stellar energy input, spiral density waves, chemistry) and that can perform the necessary radiative transfer, all at high enough resolution, are needed. So are careful experiments which allow disentangling the effects of all those ingredients, and of the average quantities versus those of the fluctuations. Consideration of the gravitational effect of the stars is also needed, which implies that hybrid gas+stars simulations are needed. Then, continuous feedback to/from observations is essential through the production of synthetic observations of the numerical models. A long, exciting way still lies ahead to a comprehensive theory that grasps the dynamics, thermodynamics and statistics of the ISM with the same level of detail with which the time-dependent and the multi-phase models grasped the thermal and radiative issues.

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